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5 Analysis of the June 15, 2013, Isolated Extreme Rainfall Event in Springfield, Missouri  
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9 W. Scott Lincoln<sup>1</sup>

10 1. National Weather Service Lower Mississippi River Forecast Center  
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34 Corresponding Author:  
35 W. Scott Lincoln  
36 NWS Lower Mississippi River Forecast Center  
37 62300 Airport Rd, Slidell, LA 70460  
38 scott.lincoln@noaa.gov  
39  
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## ABSTRACT

An isolated extreme rainfall event occurred across portions of the Springfield, Missouri, area on June 15th, 2013, causing substantial flooding of several small headwater tributaries of the James River. Heavy, nearly-stationary thunderstorm activity developed along an outflow boundary after 1500 UTC. This area of thunderstorms trained over south Springfield before dissipating around 1845 UTC. Post-event analysis of rainfall amounts indicated both gauge observations and radar-derived estimates exceeding the 100 year (1% annual chance equivalent) event. Local storm reports from the National Weather Service (NWS) forecast office in Springfield were supplemented with additional reports derived from news media and social media. Flash flood nowcasting techniques such as NWS Gridded Flash Flood Guidance (GFFG), rainfall average recurrence interval (ARI) estimates, the Distributed Hydrologic Model Threshold Frequency (DHM-TF), and the Flooded Locations and Simulated Hydrographs Project (FLASH) were compared to local storm reports of flash flooding. A timeline of output from each of these techniques was compared to the time of reported flooding to evaluate the usefulness of each tool in the context of NWS operations. It was found that GFFG underestimated the severity of the flash flooding. Rainfall ARI estimates, DHM-TF, and FLASH each suggested a significant flash flood event, however DHM-TF output would have been available too late for forecasters and FLASH output would have provided several areas of false alarms. Rainfall ARI estimates provided the best balance of detecting areas of flash flooding, correctly estimating flash flood severity, and being available in a timely manner to NWS forecasters.

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## 1. Introduction

An isolated extreme rainfall event occurred across portions of the Springfield, Missouri, area on June 15<sup>th</sup>, 2013, causing substantial flooding of several small headwater tributaries of the James River. Isolated areas were analyzed to be at least a 100 yr (1% annual chance equivalent) event when looking at both two hour and three hour durations. There was very little lag time between the periods of heaviest rainfall and the worst impacts of flash flooding. This case study provides a meteorological overview of the event and also discusses operational forecasting considerations, with an emphasis on information available to warning forecasters prior to the onset of flooding.

## 2. Meteorological Aspects

### *2a. Synoptic Analysis*

The origins of the thunderstorm activity directly responsible for this event lie with a line of storms that formed in Nebraska and Iowa on June 14<sup>th</sup>. At 0300 UTC on June 15<sup>th</sup>, a surface low was analyzed near Omaha, NE, with an associated weak warm front and stationary front extending southward toward the gulf coast (Figure 1). The cluster of storms evolved into a squall line overnight, with the activity turning toward a SSE motion almost parallel to the front. By 0900 UTC, the line of thunderstorms was decaying as it moved into central Missouri and an outflow boundary was analyzed along the leading edge of the activity (Figure 2). The low pressure area and associated stationary front had moved little over the six hour period. By about 1200 UTC, most of thunderstorm activity had ceased along the outflow boundary except for the western portion which had slowed in its southern propagation. Over the three hour period from roughly 1200 UTC to 1500 UTC, thunderstorm activity decreased in aerial coverage but increased in intensity just to the north of the Springfield area. The heaviest activity was sitting over the northeast sections of Springfield by approximately 1400 UTC and was moving very slowly eastward, with storms continuing to build toward the southwest.

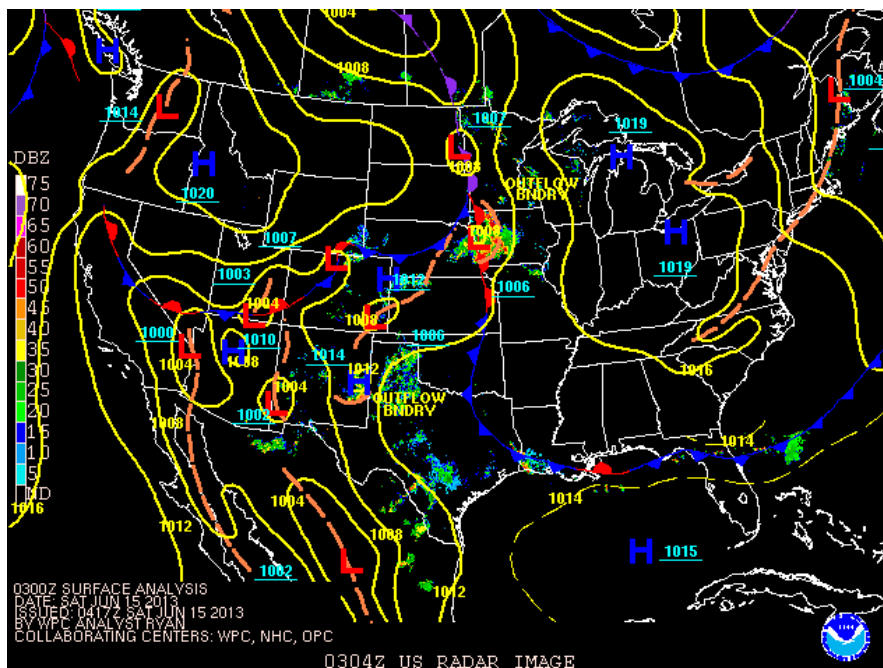


Figure 1. HPC surface analysis and radar composite for 0300 UTC June 15th, 2013.

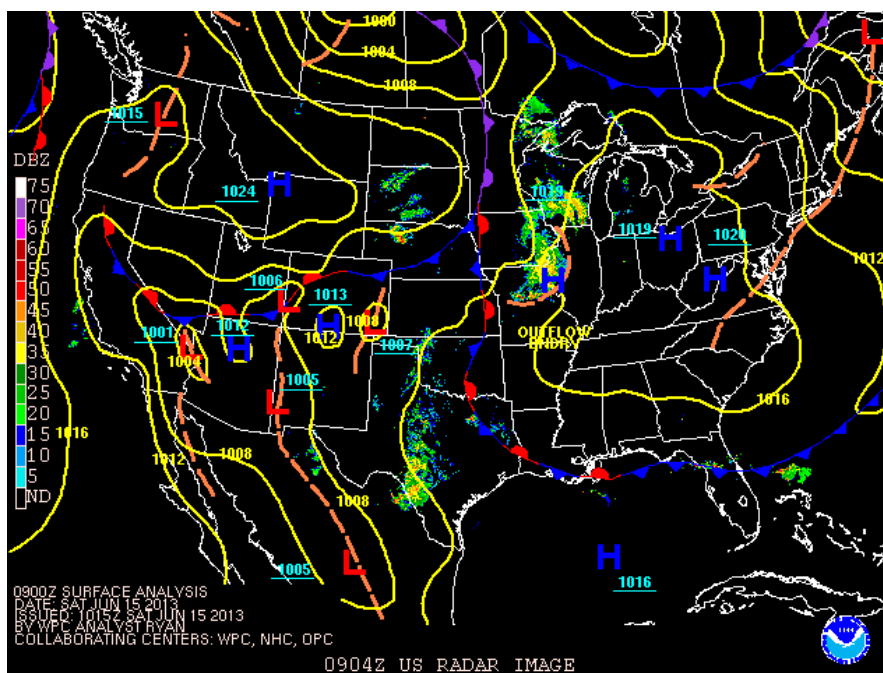


Figure 2. HPC surface analysis and radar composite for 0900 UTC June 15th, 2013.

Surface winds were light through the event, generally 5 knots or less. The 1200 UTC sounding from NWS WFO Springfield (located on the northwest side of the city) indicated generally light winds up to about the 400 mb level, above which winds were 30-45 knots out of the west (Figure 3). The 0 C and -20 C levels were approximately 13,210 ft and 22,170 ft, respectively. The sounding profile was rather moist, although the precipitable water (1.64 inches) was not particularly anomalous for June (80<sup>th</sup> percentile). Springfield was on the edge of a steep gradient toward higher precipitable water to the northwest, closer to the surface low in the upper Midwest. Southwest Missouri was in an area of very light mid-level winds just east of a 500mb shortwave (Figure 4).

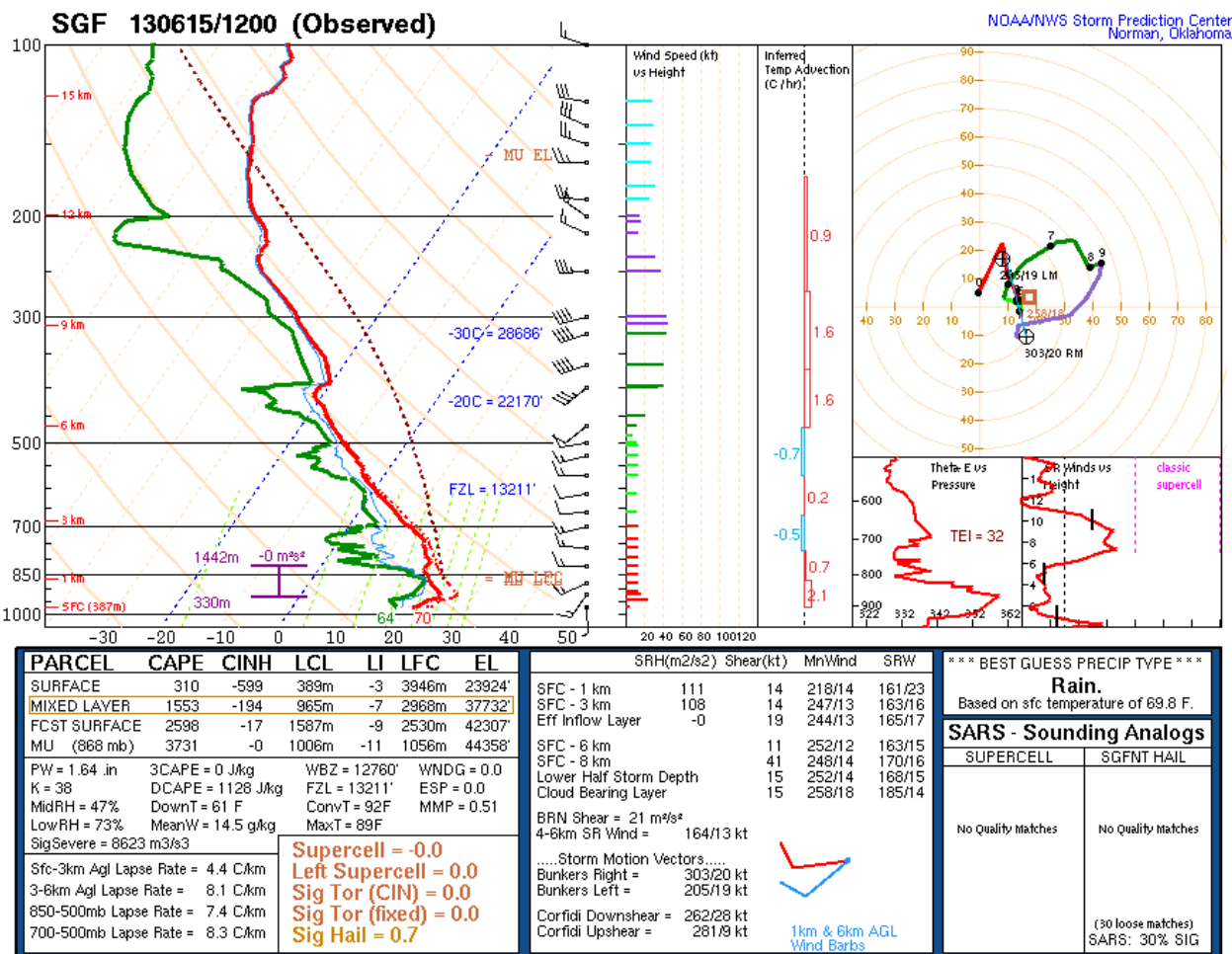


Figure 3. Sounding for June 15, 2013, 1200 UTC launch from NWS WFO Springfield.

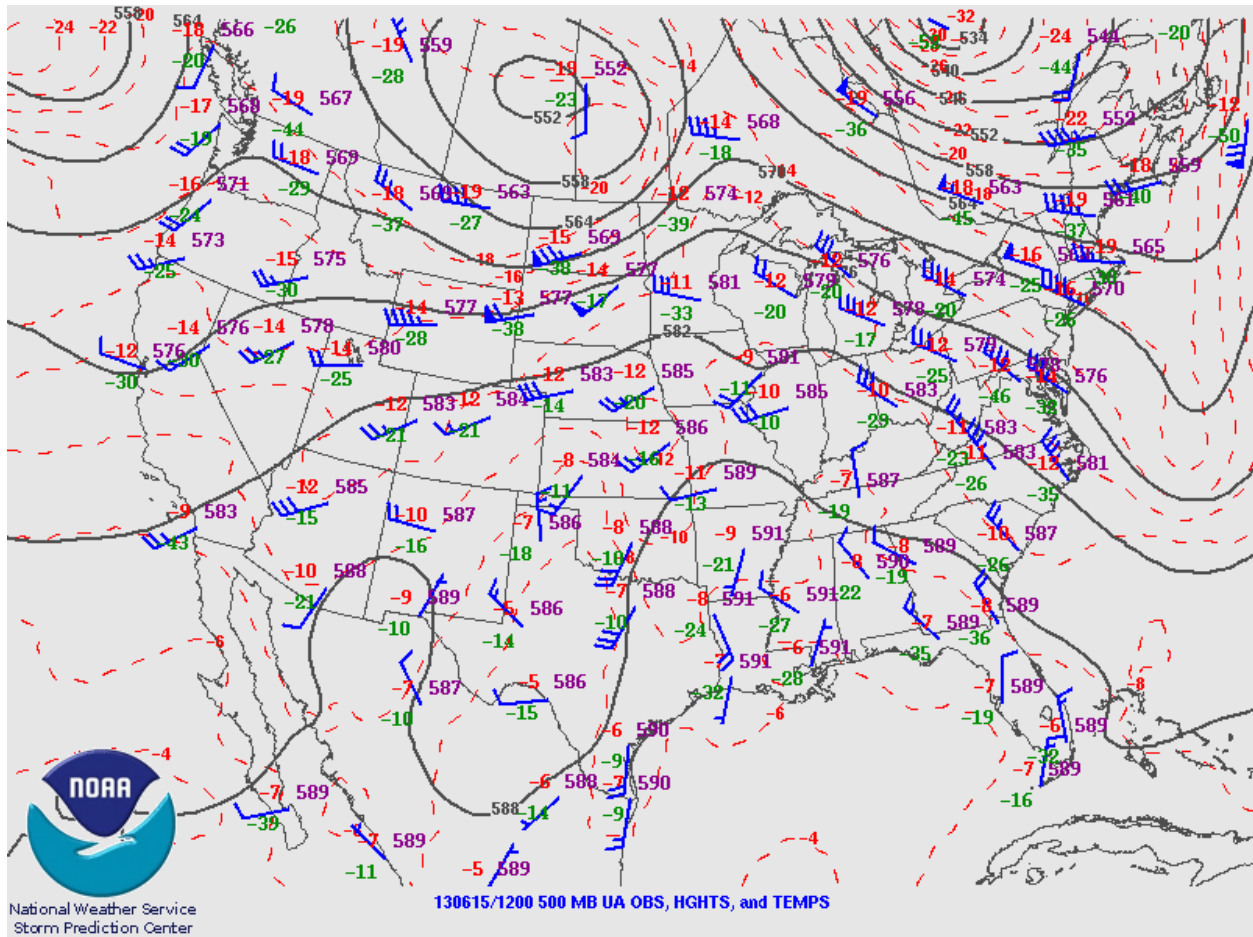


Figure 4. Upper air analysis for the 500mb level valid June 15, 2013, at 1200 UTC.

## 2b. Radar Analysis

The thunderstorms directly responsible for producing the flash flood activity had formed by about 1500 UTC. One area of heavy rainfall was located just east of Springfield with another area forming on the south side of the city (Figure 5a). These thunderstorms were nearly stationary. By 1600 UTC, the storm over southern Springfield became dominant and had stalled (Figure 5b). Thunderstorm activity continued to develop over the same area of south Springfield for nearly three hours (1545 UTC to 1845 UTC) until dissipating.

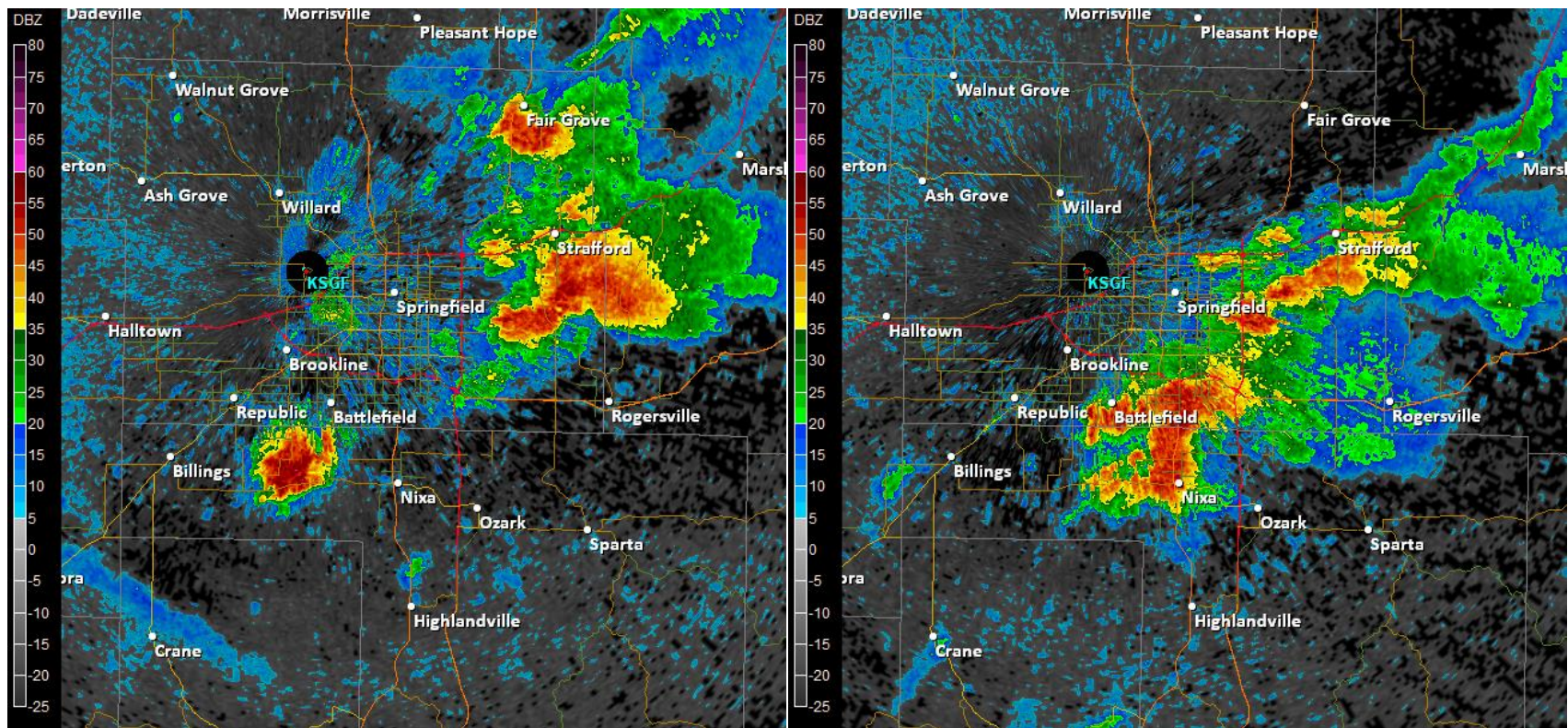


Figure 5. NEXRAD reflectivity from site KSGF for the Springfield, MO, area at approximately 1500 UTC (left) and approximately 1600 UTC (right).

According to radar data from site KSGF, the highest rainfall rates occurred over the far southern portions of Springfield near the Greene/Christian County line, just southwest of the James River Freeway (US60) and Schoolcraft Freeway (US65) interchange. Reflectivity values from the 0.5 degree tilt typically ranged from 50-55 dbz with a few areas exceeding 60 dbz. Differential reflectivity varied substantially; values ranged from 1.0-5.0 db, but were many times at the lower end of the range in the highest reflectivity areas. This may be due to small hail mixed with rainfall. Correlation coefficient values were typically 0.95-1.00 and rarely dropped below 0.90. Specific differential phase was typically in the 1.0-3.0 deg/km range, but did briefly exceed 5.0 deg/km in a few isolated areas. Vertical cross sections of reflectivity during the times of highest rainfall rates showed high reflectivity values (sometimes >60dbz) above the 0C level and nearing the -20C level (Figure 6). All of these factors described above suggest that this event was mostly dominated by cold rain processes. The extreme nature of the event was due to nearly-stationary, thunderstorms training over the same locations for a multiple hour period.

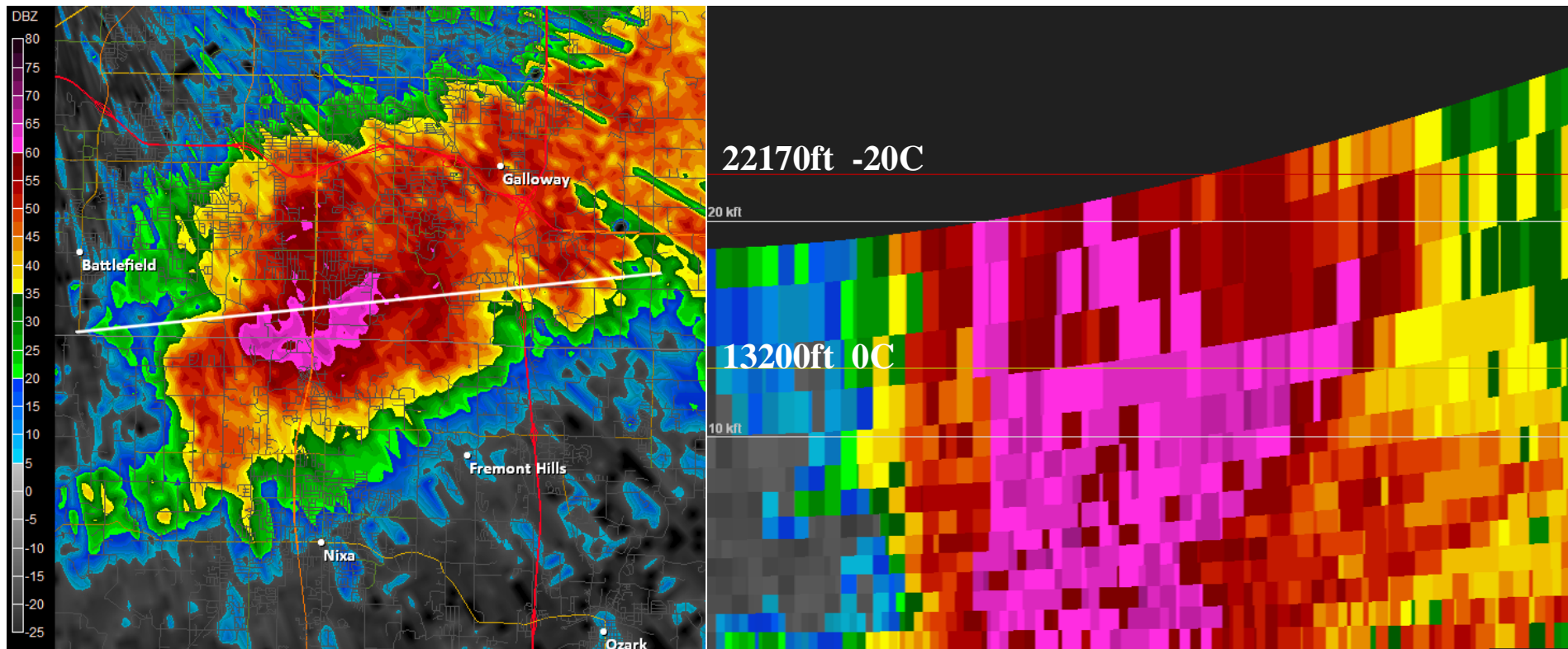


Figure 6. NEXRAD reflectivity from site KSGF zoomed in on south Springfield, MO, at approximately 1635 UTC one periods of highest rainfall rates (left) and a vertical cross section of reflectivity from the associated volume scan (right). Notice high reflectivity values (>60dbz) extending well above the 0C level to near the -20C level.

### 3. Rainfall Estimation

Rainfall data from numerous sources was obtained and analyzed for the period of heaviest rainfall on June 15<sup>th</sup>, 2013. Rainfall data can be subdivided by its spatial coverage, meaning either point data (such as from a rain gauge) or gridded data (such as from remotely-sensed estimates). Some of this data is available to forecasters in realtime and some data is only available after an event. This section elaborates on the different types of data used in this analysis. First is point rainfall data from official sources, then point rainfall data from partner agencies and the public, followed by gridded rainfall estimates.

#### *3a. Point Rainfall Data*

Point rainfall data was first obtained from official sites, which include the Automated Surface Observing System (ASOS; automated stations typically located at airports), United States Geological Survey (USGS; automated stations co-located with river observations), NWS Cooperative Observer Program (COOP; typically manual-reporting daily stations used for NWS climate records), and National Climatic Data Center (NCDC; long term climate reporting stations). Of these, information from ASOS and USGS sites would typically be available in realtime to NWS forecasters. Next, point rainfall data was obtained from unofficial sites from partner agencies, which include City of Springfield Public Works (automated gauges used for stormwater engineering) and the Community Collaborative Rain Hail and Snow Network (CoCoRaHS; typically manual-reporting daily stations monitored by a volunteer observer network). Of these, information from the Springfield rain gauge network would typically be available in realtime to NWS forecasters. Finally, point rainfall data was obtained from private sites, which include Weather Underground Personal Weather Station sites (WU PWS; automated stations of varying quality and reliability run by private persons or groups), local storm reports from trained spotters (LSR; rainfall measured, via unknown means, by NWS-trained persons, and called in to a local NWS office), and LSRs from the general public (rainfall measured, via unknown means, by persons of unknown training, and



after selecting relevant sites using methodology from “2012 Southeast Louisiana and Southern Mississippi Flooding Due to Hurricane Isaac” (Lincoln, et al., 2013). Storm total rainfall from all of these different data sources is illustrated by Figure 8. The rainfall reported at Cherokee Middle School (6.19 in) is considered to be an isolated maximum. Two LSRs provided to NWS forecasters estimated rainfall totals of approximately 7.5 inches and 9.0 inches, but their reported location put them very close to rainfall gauges that reported much lower totals (3.87 to 4.86 inches). Because their exact location could not be determined with high confidence, and because the reports were not consistent with other gauges in the area, they were not plotted.

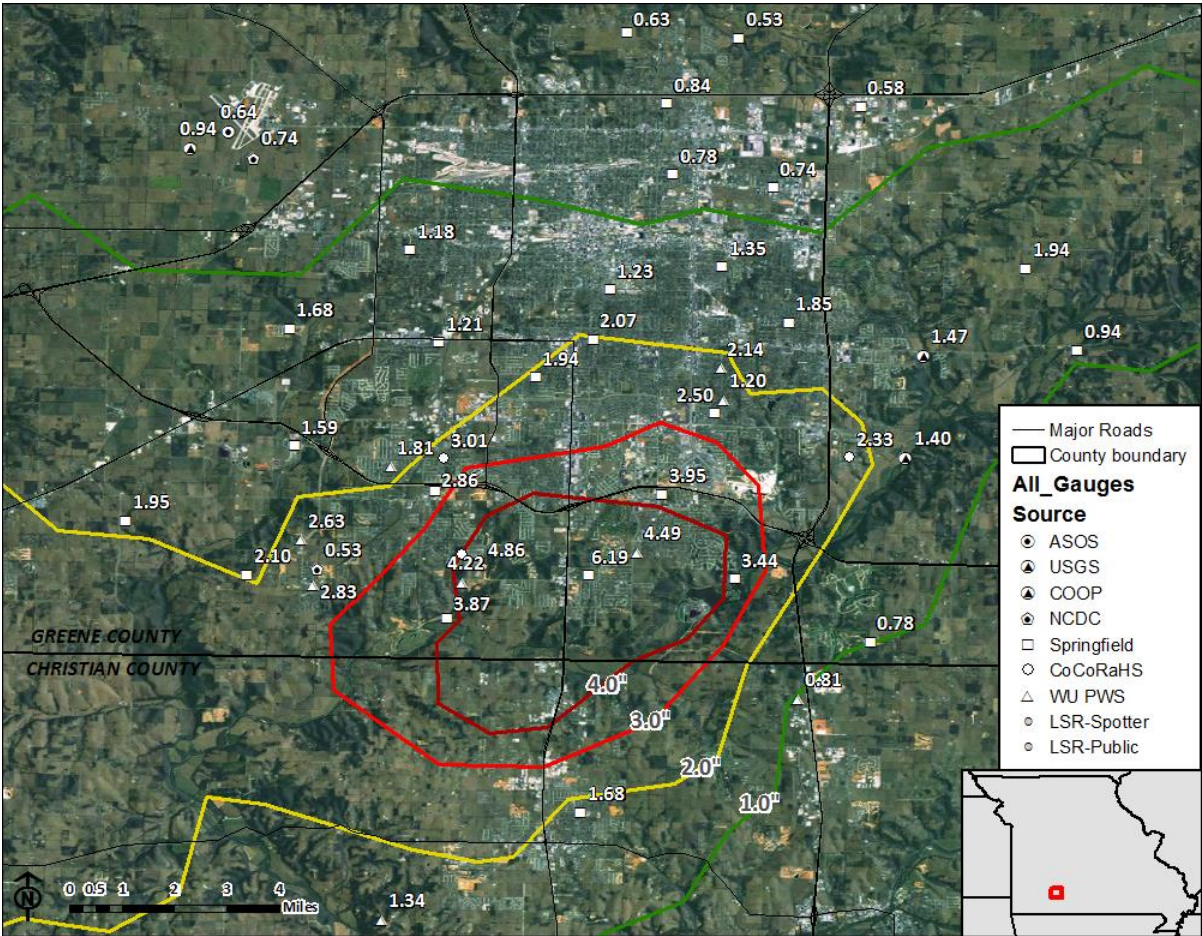


Figure 8. Storm total rainfall for June 15<sup>th</sup>, 2013, from all rainfall gauges. Symbols represent the different sources of rainfall data. Subjective contour analysis of gauge data was added as a reference.

3b. Gridded Rainfall Data

Dual-pol NEXRAD data provide some of the quickest rainfall estimates available to NWS warning forecasters. The recently added capability for dual polarization (radar pulses sent with both horizontal and vertical polarization) has improved the capability for forecasters to discriminate between spherical rain drops, elongated rain drops, and rainfall mixed with hail – each of which has a different precipitation rate for a given reflectivity return. The biggest strength of these estimates is that they are available for warning forecasters within minutes of the rainfall being detected by radar. Storm total rainfall from the dual-pol QPE product is illustrated by Figure 9.

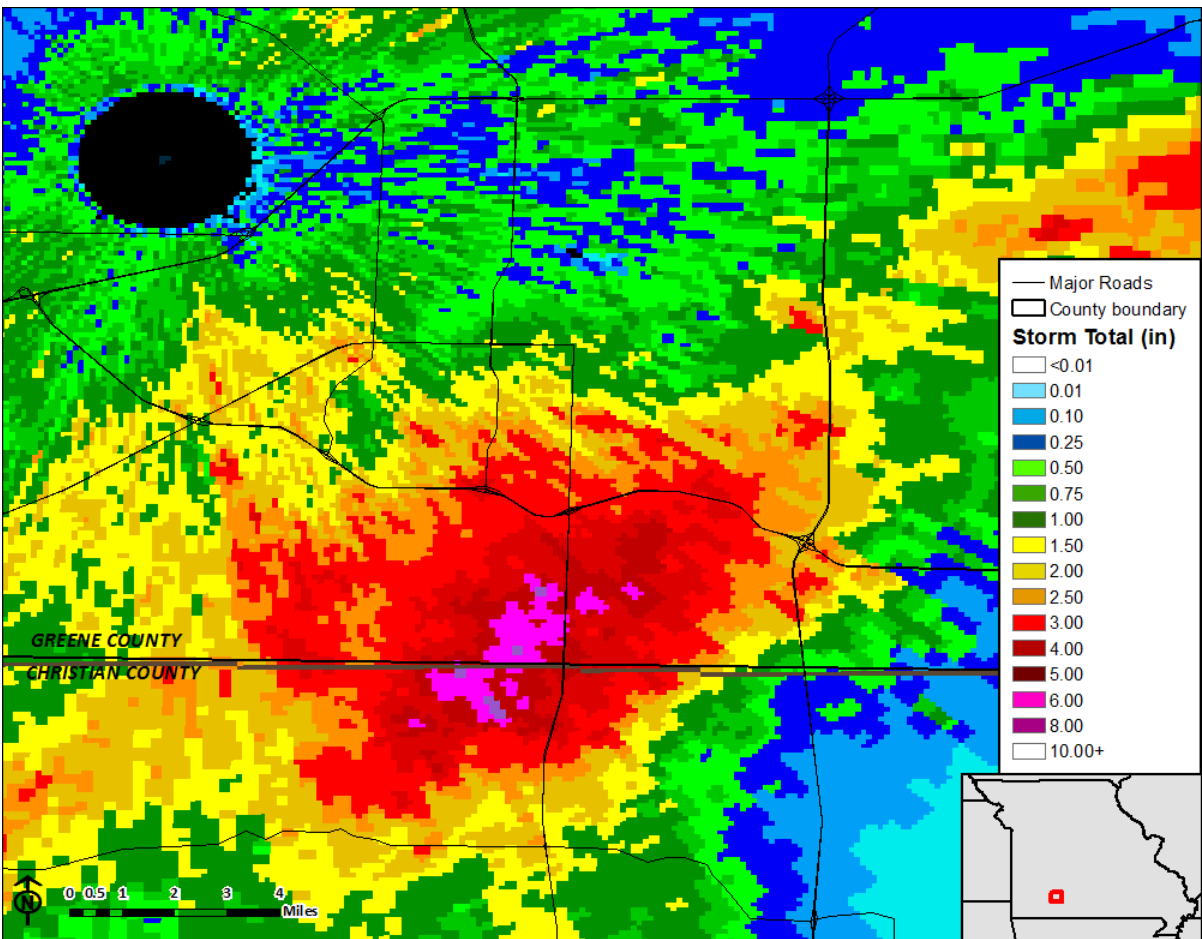


Figure 9. Storm total rainfall for June 15th, 2013, from the dual-pol QPE product.

Another radar-derived precipitation estimate available to forecasters in near-realtime is Q2 (called Q3 since fall 2013), produced by the National Severe Storms Laboratory's (NSSL) Multi-Radar Multi-Sensor System (MRMS). Q2 differs from dual-pol radar estimates in that it is derived from multiple radars that have been seamlessly mosaicked. Short-term model data is compared with the character of radar reflectivity to determine the best radar-rainfall relationship. Storm total rainfall from the Q2 QPE product is illustrated by Figure 10.

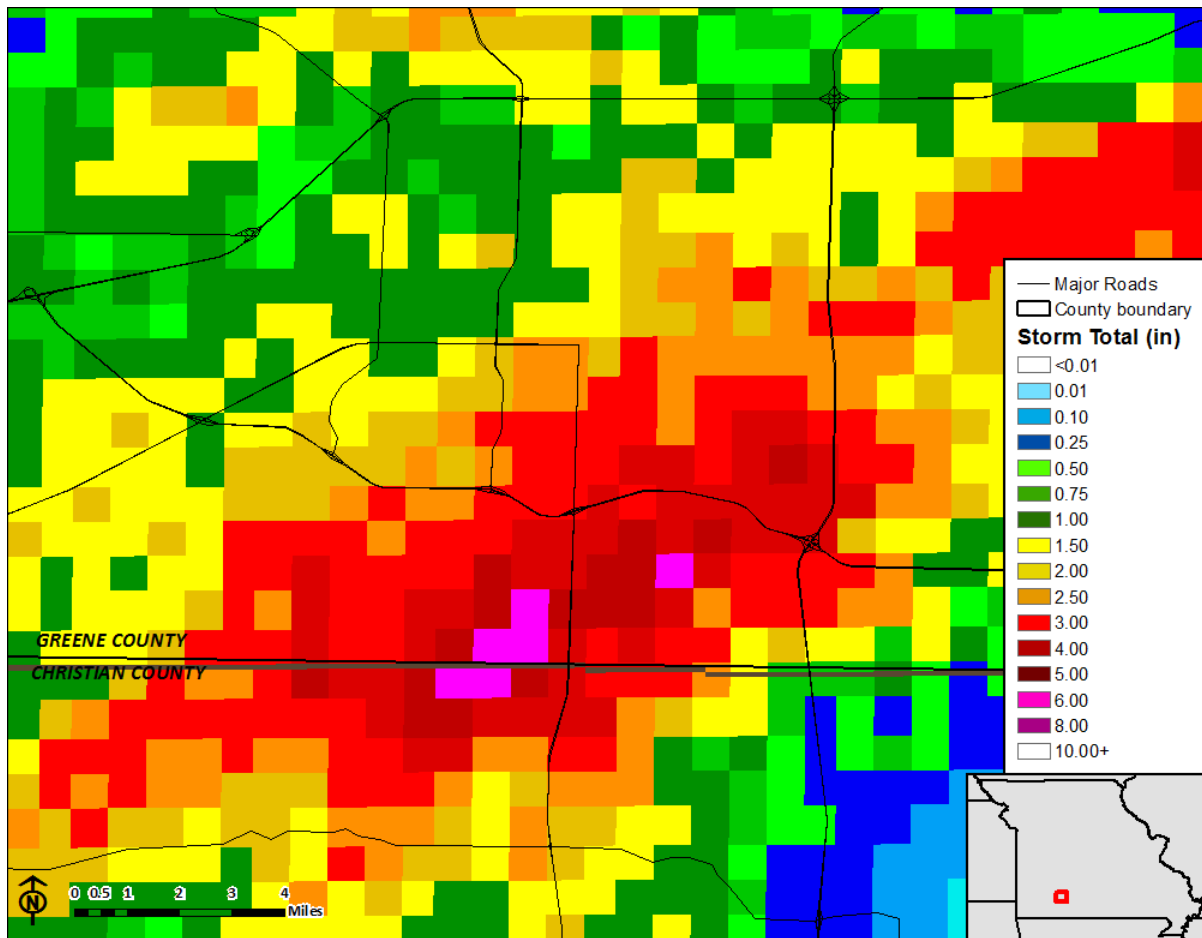


Figure 10. Storm total rainfall for June 15th, 2013, from the MRMS Q2 product.

The official quantitative precipitation estimate (QPE) product created by the NWS River Forecast Centers (RFCs) is referred to as the multi-sensor best-estimate rainfall, and is created by mosaicing gridded radar estimates from individual radar sites, bias correcting the grids with automated rain gauges, then subsequently quality controlling the grids every hour. Hourly and daily data was obtained in GIS format from the NWS Advanced Hydrologic Prediction Service (AHPS) precipitation page (<http://water.weather.gov/precip/>, Nov 2013). Storm total rainfall from the NWS QPE product is illustrated by Figure 11.

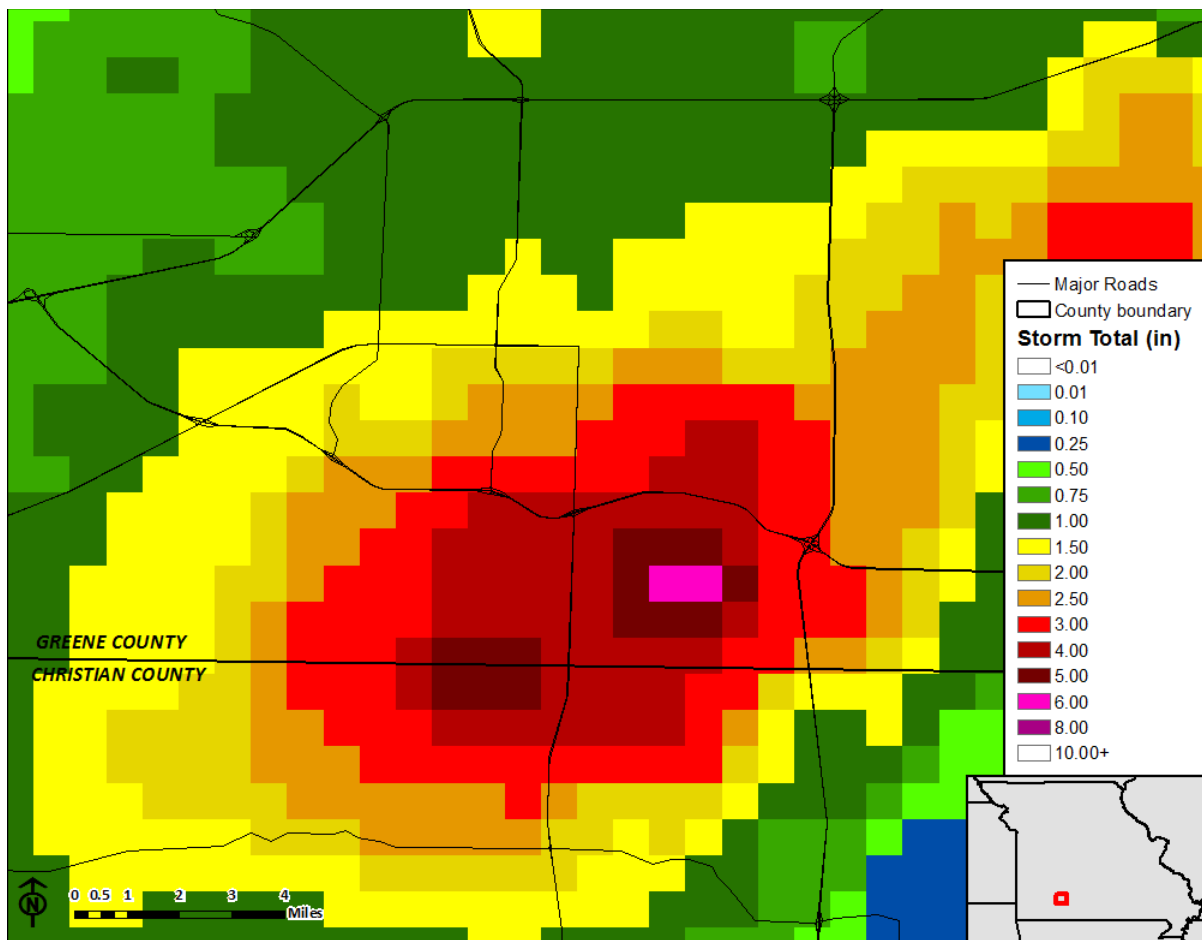


Figure 11. Storm total rainfall for June 15<sup>th</sup>, 2013, from the official NWS QPE product.

The availability of rapidly-updating, accurate precipitation estimates are vital to flash flood nowcasting, however this presents a dilemma. Estimates from dual-pol radar data and MRMS update quickly, but substantial biases may exist due to the use of remotely-sensed data and imperfect algorithms. Rain gauges can help correct these biases, but typically do not update as quickly as the radar data itself. Estimates from the RFC-produced rainfall product are generally considered more accurate due to the inclusion of rain gauge bias correction, however these estimates are only produced once per hour, and there is a 30 minute delay before processing begins to allow rain gauge data to be transmitted into NWS systems. Thus, these official QPE estimates range from half an hour (0.5) to one and a half (1.5) hours old by the time they are first available to warning forecasters for use in realtime operations. This dilemma causes all flash flood nowcasting techniques to either 1) use data with varying levels of uncertainty or 2) risk providing no lead time during a flash flood. Thus, it is important to understand which rainfall estimate is driving a particular flash flood nowcasting technique to better understand its limitations.

### *3c. Rainfall Frequency Analysis*

Gridded rainfall estimates can be compared to gridded rainfall frequency data to estimate the average recurrence interval (ARI) of this storm occurring in this location. The ARI is the average period of time between events of a given magnitude, when averaged over a very long period of time. The annual probability of a given event is equivalent to one divided by the ARI. A higher ARI, or lower annual percent chance, suggests a less frequent event; the frequency of an event has a rough correlation to event severity. ARI rainfall estimates are available from NOAA Atlas 14 produced by the NWS Hydrologic Design Studies Center (National Weather Service, 2013). The HDSC computes ARI rainfall estimates for storms with durations ranging from five (5) minutes to 60 days. Of these numerous storm durations, the 30 minute, 1 hour, 2 hour, and 3 hour durations are most relevant to this analysis.

The entire rainfall event lasted from 3-6 hours across the Springfield area, with almost all rainfall occurring over a three (3) hour period and most rainfall occurring over a two (2) hour period. The

maximum three (3) hour and two (2) hour rainfall accumulations were calculated for each rain gauge site, when possible (the maximum two and three hour accumulation time periods were not necessarily the same for each gauge site). These values were then interpolated to a grid using the Kriging method, and compared to ARI data from HDSC. The analyzed ARIs for both the two and three hour durations are illustrated by Figure 12. ARIs were very similar with both storm durations when looked at on a gridded basis, although the ARI for Cherokee Middle School was 1000 yr (0.1% annual chance equivalent) for the heaviest two hour rainfall. Using either duration, the event could be classified as extreme (using 1% annual chance event threshold) for an area approximately four miles across (east-west) and three miles across (north-south).

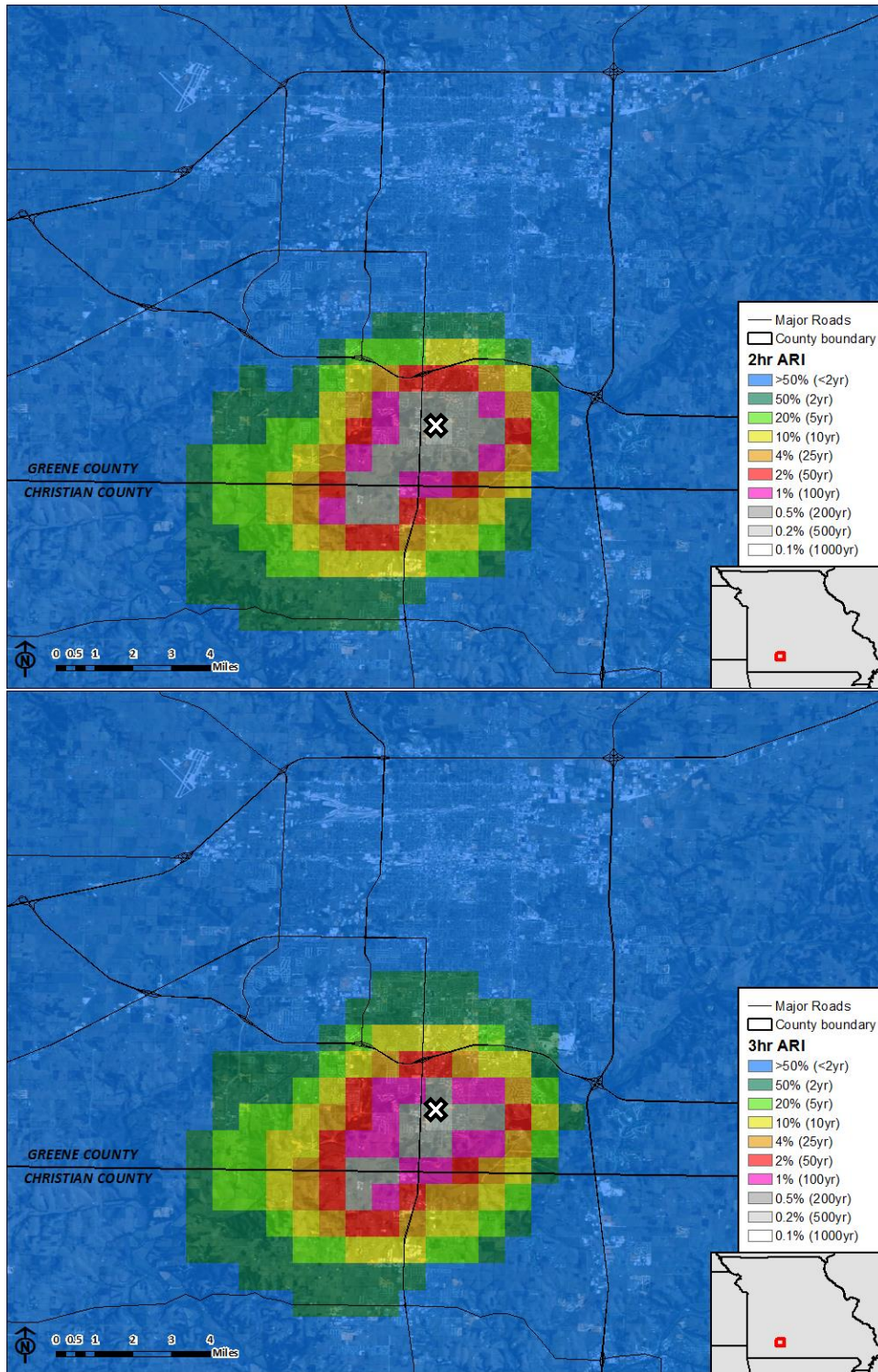


Figure 12. Estimated ARIs for the highest two hour rainfall (top) and highest three hour rainfall (bottom) during the June 15, 2013, event. Using either duration, the event could be classified as extreme (using 1% annual chance event threshold) for an area approximately four miles across (east-west) and three miles across (north-south). Both rainfall durations had an isolated maximum near Cherokee Middle School (marked with "X") of 0.2%, although the site reported rainfall matching the 0.1% event over the two hour duration.

Reports of flooding can also be compared to the rainfall frequency analysis to see how well the magnitude of the rainfall event compared to the magnitude of reported flooding. LSRs for the June 15<sup>th</sup>, 2013, flash flood event were obtained from Iowa State University's (ISU) Iowa Environmental Mesonet (IEM). Some manual quality control was required due to the coarse latitude and longitude resolution used by NWS records and due to some obvious discrepancies between the described locations and their coordinates. When possible, the storm report remarks were used to move the flash flood reports to the correct location. Additional reports were added based upon photos from local media outlets such as the Facebook account of KOLR-TV and the Ozarks News-Leader newspaper, as well as videos posted by the public to Youtube. Flooding was subjectively categorized by this author according to relative severity, ranging from least severe to most severe:

1. Minor nuisance flooding of roadways was classified as "Street Flooding"
2. Flooding of roadways deep enough to stall cars, or overtopping of bridges along major highways, were classified as "Significant Street Flooding"
3. Reports of persons needing to be rescued from residences or their vehicles were classified as "Water Rescue"
4. Evidence of water nearing or exceeding the FEMA-designated 1%/100yr floodplain were classified as "1% Floodplain"
5. Reports of residences flooding were classified as "Residence Flooded"
6. Reports of roadways being washed out due to quickly-moving flash flood waters were classified as "Washout"
7. Evidence of water nearing or exceeding the FEMA-designated 500 yr (0.2% annual chance equivalent) floodplain were classified as "0.2% Floodplain"
8. Flooding reports with little additional information were classified as "Unkown"

Almost all reports of flooding matched closely to the area of three hour rainfall ARIs exceeding a 2 yr (50% annual chance) event, with a general tendency for the most severe flooding reports to be toward the areas of more extreme rainfall (Figure 13). The one exception to this would be the report of a water rescue at the James River Freeway interchange with Sunshine Avenue. This water rescue appears to have occurred outside of the 2 yr event area. This section of the James River Freeway is relatively new and it seems unusual for a newly-constructed arterial to be overwhelmed by rainfall that is not uncommon. It should also be noted that the James River runs right through the middle of the hardest hit area, limiting the flash flood reports in that area. After quality control of LSR locations, it was found that the reports of flooding aligned closely with natural streams and drainages (Figure 14).

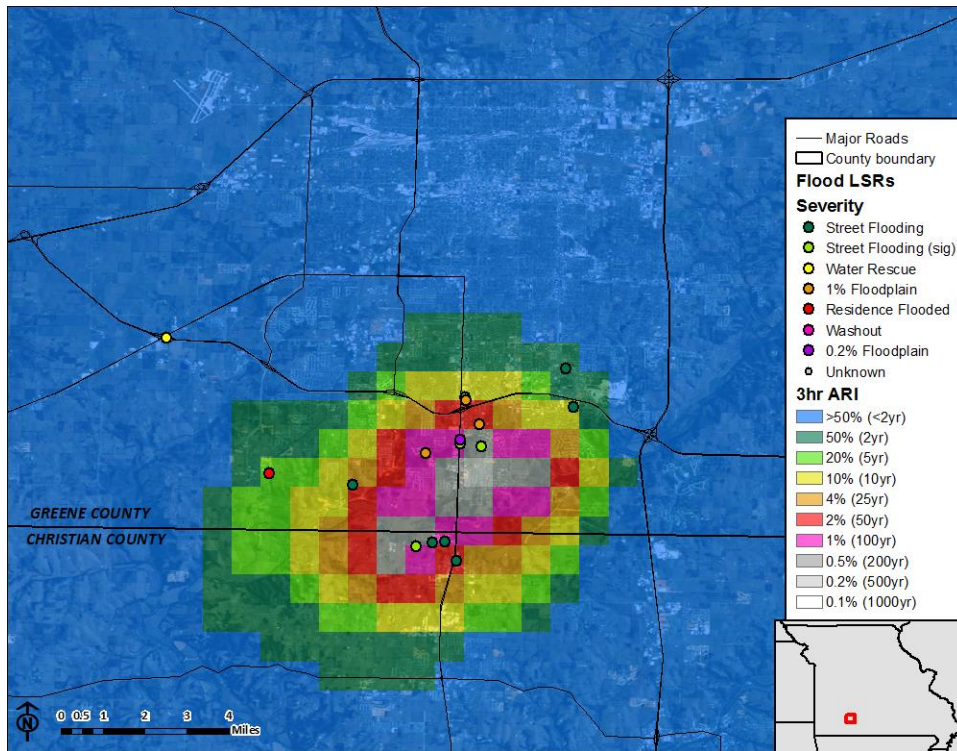


Figure 13. Estimated three hour ARIs compared to reports from flooding. Flooding reports are subjectively ranked by severity (see discussion).

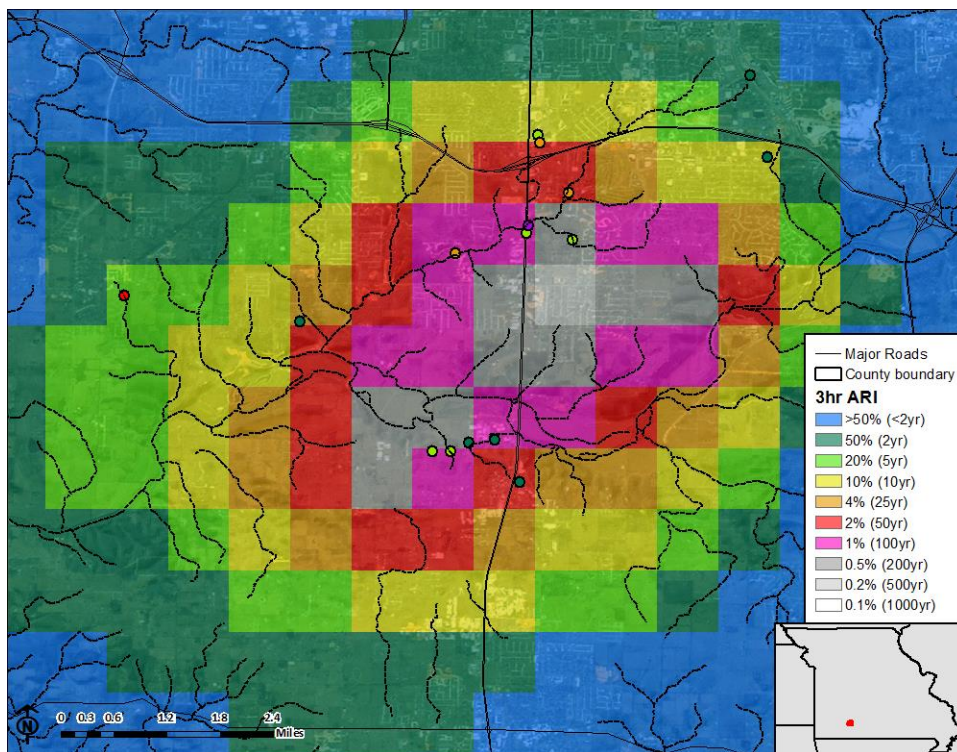


Figure 14. Same as Figure 13, but zoomed in on area of worst flooding, with small streams added for reference.

## 4. Operational Forecast Considerations

### *4a. Flash Flood Nowcasting Techniques Available to NWS Warning Forecasters*

Gathering all possible data for an analysis is certainly helpful in the context of accurate hindcasting, however many data sources would not have been available just prior to the event when forecasters would need that information for a critical warning decision. To improve our forecasting and nowcasting of extreme flood events, we must only evaluate the data that would have been available to a forecaster at the time of the forecast or nowcast. In regards to the June 15<sup>th</sup>, 2013, flash flood event in south Springfield, MO, some information was suggestive of not only flooding but uncommon flooding several minutes before reports were communicated to NWS offices. Other information available to forecasters before the event was less conclusive. Some tools available to NWS forecasters applicable to forecasting this type of flood event include realtime rainfall estimates from dual-pol NEXRAD data, realtime rainfall estimates from NSSL's MRMS system, the gridded flash flood guidance (GFFG) produced by the NWS River Forecast Centers, the comparison of rainfall estimates to analyzed rainfall frequency data (discussed in section 3c. Rainfall Frequency Analysis), output from the experimental Distributed Hydrologic Model Threshold Frequency (DHM-TF), and output from the experimental Flooded Locations and Simulated Hydrographs Project (FLASH). The various rainfall estimates were previously discussed (section 3. Rainfall Estimation) and will not be elaborated on in this section.

GFFG is produced four times daily (00 UTC, 06 UTC, 12 UTC, 18 UTC) by NWS RFCs and provides a rainfall threshold (over one, three, and six hour storm durations) which, when exceeded, is expected to cause flash flooding. GFFG is derived from gridded land use and soil data, and varies based upon changes in modeled soil moisture. GFFG is ingested into the Flash Flood Monitoring and Prediction (FFMP) software at NWS weather forecast offices, where it is averaged over small stream basins and compared to office-defined rainfall estimates in realtime.

The DHM-TF is an experimental flash flood nowcasting technique developed at the NWS's Office of Hydrologic Development (Cosgrove, et al., 2012) which models surface water runoff from RFC rainfall. The DHM-TF compares modeled surface water flow in realtime to modeled surface water flow over the period of record (the length of available rainfall data) to estimate a ARI at each grid cell. Thus, this technique is in contrast to rainfall ARIs in that it indicates where runoff is accumulating rather than where it is generated; because of this, the DHM-TF should be more directly comparable to the severity of flooding than rainfall ARIs. This methodology also reduces uncertainty from lack of calibration by comparing realtime, biased output to historical, biased output. Unfortunately, the DHM-TF is driven by the RFC rainfall estimates which can introduce a lag time of up to 1.5 hours between rainfall hitting the ground and model output becoming available. The maximum streamflow ARIs from the DHM-TF compared to the flooding LSRs are illustrated by Figure 15. Streamflow in the pixels representing Ward Creek reached ARIs up to 25 yr (4% annual chance equivalent), which is considered significant for this technique because the underlying baseline period of record is only about 10 years in length (Brian Cosgrove, personal communication, 2013). Also of note is the cluster of flood reports south of Ward Creek that are in an area of 2 yr (50% annual chance equivalent) or less. This grid cell represents the James River, which has a much larger contributing area than Ward Creek, and most of which received only light rainfall.

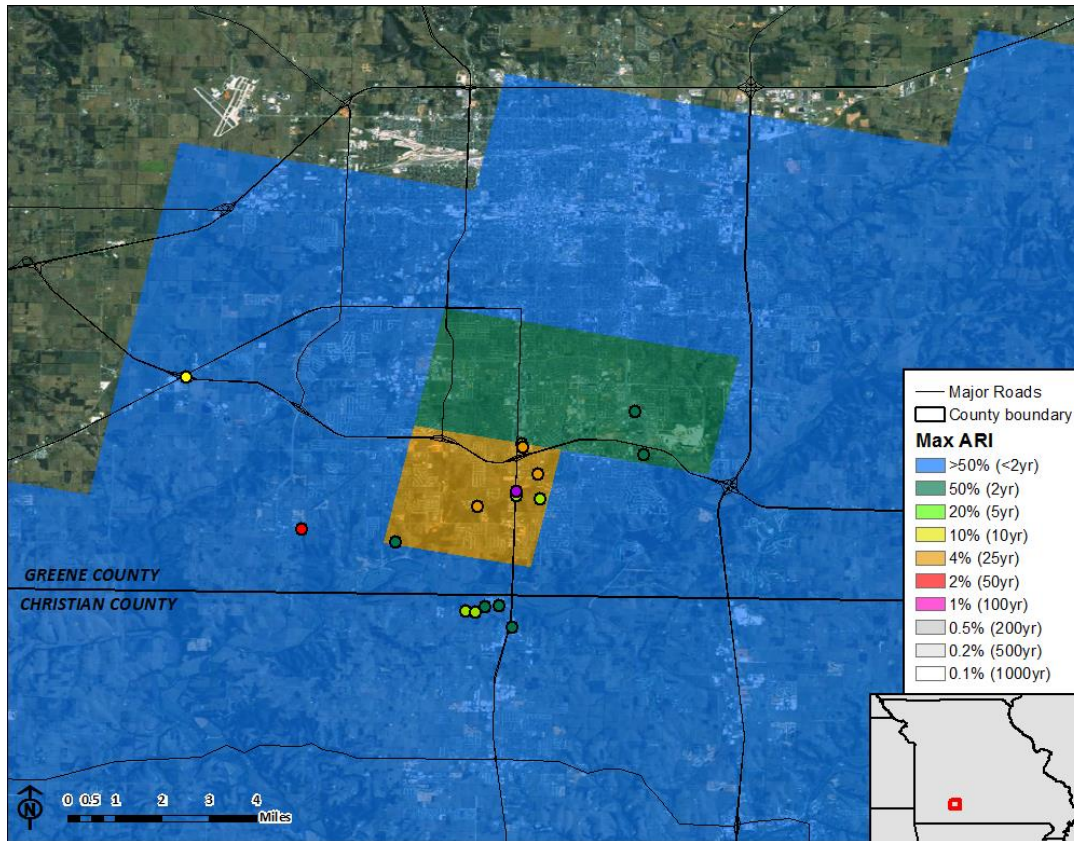


Figure 15. Maximum streamflow ARIs from DHM-TF compared to reports of flooding. Flooding reports are subjectively ranked by severity (see discussion).

The FLASH project is an experimental flash flood nowcasting technique similar to the DHM-TF in that it attempts to model where runoff accumulates and compares surface water flow to historical conditions (<http://blog.nssl.noaa.gov/flash/>). FLASH differs in rainfall forcing; it is driven by estimates from the Q2 rainfall product instead of the RFC QPE rainfall product used by DHM-TF. FLASH updates more quickly but may be susceptible to higher uncertainty due to the higher uncertainty in the rainfall data. The maximum streamflow ARIs from the FLASH project compared to the flooding LSRs are illustrated by Figure 16. Output from FLASH suggested that many portions of Springfield would experience flooding, exceeding the 200 yr (0.5% annual chance equivalent) in some areas. ARIs of this magnitude are far beyond values considered significant for this technique because the underlying baseline

period of record is also about 10 years in length (see DHM-TF discussion above). In many cases, the modeled areas of worst flooding did not line up with the storm reports of flooding.

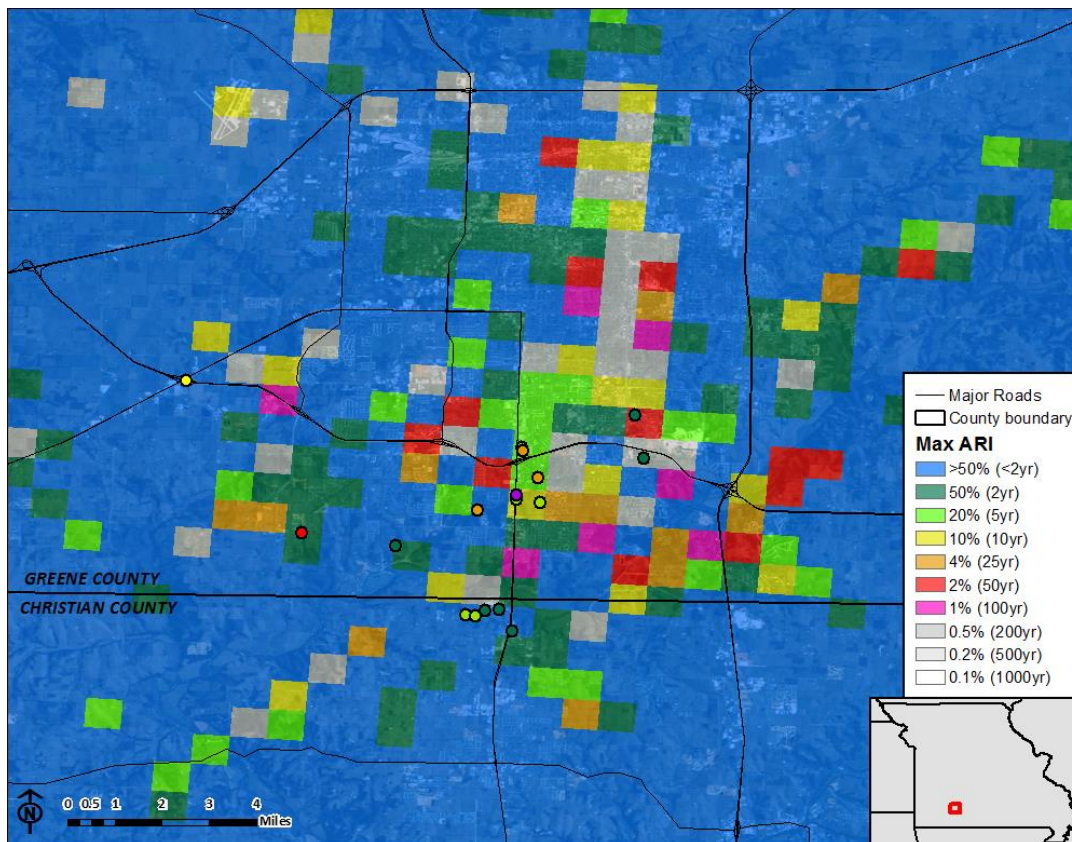


Figure 16. Maximum streamflow ARIs from FLASH compared to reports of flooding. Flooding reports are subjectively ranked by severity (see discussion).

#### 4b. June 15<sup>th</sup> Flash Flood Timeline

The first local storm reports came in to the NWS WFO Springfield office around 1717 UTC on June 15<sup>th</sup> and these reports continued to come in through about 1900 UTC. For the purposes of this analysis, 1715 UTC is considered to be the onset of flash flooding of high enough severity to warrant a report to the NWS. The following sections analyze what information would have been available to NWS forecasters with varying degrees of lead time. Lead times of 15 and 30 minutes are compared to running accumulations of rainfall in Figure 17.

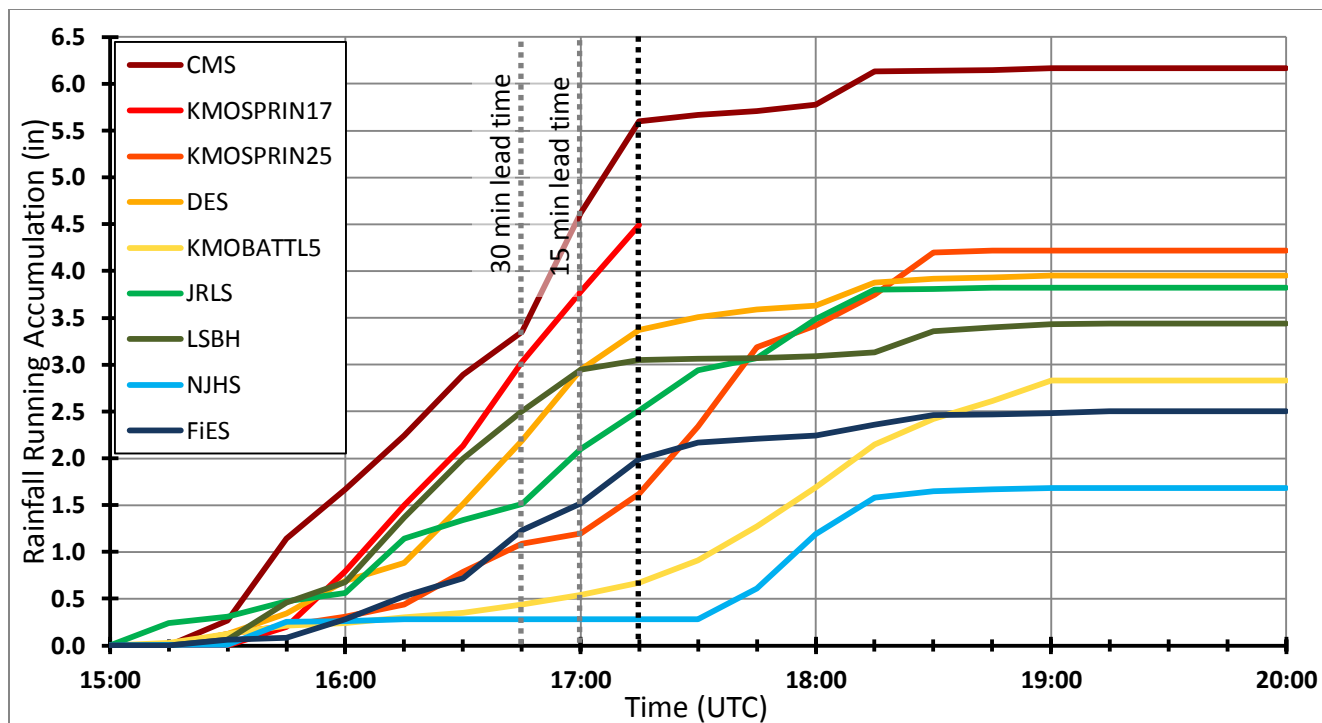


Figure 17. Running rainfall accumulation for several rain gauge sites in the the area of heaviest rainfall (~2.5 inches or greater). The onset set of flooding (black dashed), 15 minute lead time (gray dashed) and 30 minute lead time (gray dashed) lines are added for reference.

### 30 MINUTES OF LEAD TIME (1645 UTC)

At 1645 UTC, NWS forecasters would have an estimated 30 minutes of lead time for the event. Heavy rainfall had been occurring near the Cherokee Middle School area for about an hour and was nearing an accumulation of almost 3.5 inches. A nearly stalled thunderstorm continues to reform over the same areas of south Springfield. NEXRAD radar indicates heavy rainfall mixed with hail (Figure 18a). One hour rainfall is barely exceeding GFFG values, but is already higher than the 50 yr (2% annual chance equivalent) event based upon historical rainfall frequency data (Figure 19a).

25 MINUTES OF LEAD TIME (1650 UTC)

Output from the DHM-TF utilizing RFC rainfall estimates ending at 16 UTC would finish processing at approximately 1650 UTC. No areas of significant streamflow are indicated by output from the DHM-TF (Figure 20a).

15 MINUTES OF LEAD TIME (1700 UTC)

At 1700 UTC, NWS forecasters would have an estimated 15 minutes of lead time for the event. Heavy rainfall had been occurring near the Cherokee Middle School area for almost an hour and a half and was nearing an accumulation of almost 4.5 inches. The nearly stationary thunderstorm remained over portions of south Springfield. NEXRAD radar continued to show heavy rainfall mixed with hail (Figure 18b). One hour rainfall is still barely exceeding GFFG values but continues to exceed the 50 yr (2% annual chance equivalent) event based upon historical rainfall frequency data (Figure 19b). Output from the experimental DHM-TF model run at the Lower Mississippi River Forecast Center (LMRFC) would not yet have taken rainfall from the 1600-1700 UTC hour into account because it depends on bias-corrected rainfall (available at about 30 minutes after the hour), and would not have provided useful estimates of flooding magnitude until 15 minutes after the first reports of flooding.

-35 MINUTES OF LEAD TIME (1750 UTC)

Output from the DHM-TF utilizing RFC rainfall estimates ending at 17 UTC would finish processing at approximately 1750 UTC. No areas of significant streamflow are indicated by output from the DHM-TF (Figure 20b).

429 -95 MINUTES OF LEAD TIME (1850 UTC)

430           Output from the DHM-TF utilizing RFC rainfall estimates ending at 18 UTC would finish  
431 processing at approximately 1850 UTC. This is the first hourly update of the DHM-TF that indicated  
432 areas of significant streamflow in the Springfield area (Figure 20c). The grid cell that covers the area of  
433 most severe flooding (Ward Branch) yielded a streamflow ARI of 9 yr (11.1% annual chance equivalent).

434

435 -155 MINUTES OF LEAD TIME (1950 UTC)

436           Output from the DHM-TF utilizing RFC rainfall estimates ending at 19 UTC would finish  
437 processing at approximately 1950 UTC. This hourly update of the DHM-TF suggested the highest  
438 streamflow ARIs; after this point streamflow ARIs for Ward Branch began to decrease (Figure 20d). The  
439 grid cell covering Ward Branch now yielded a streamflow ARI of 27 yr (3.7% annual chance equivalent).

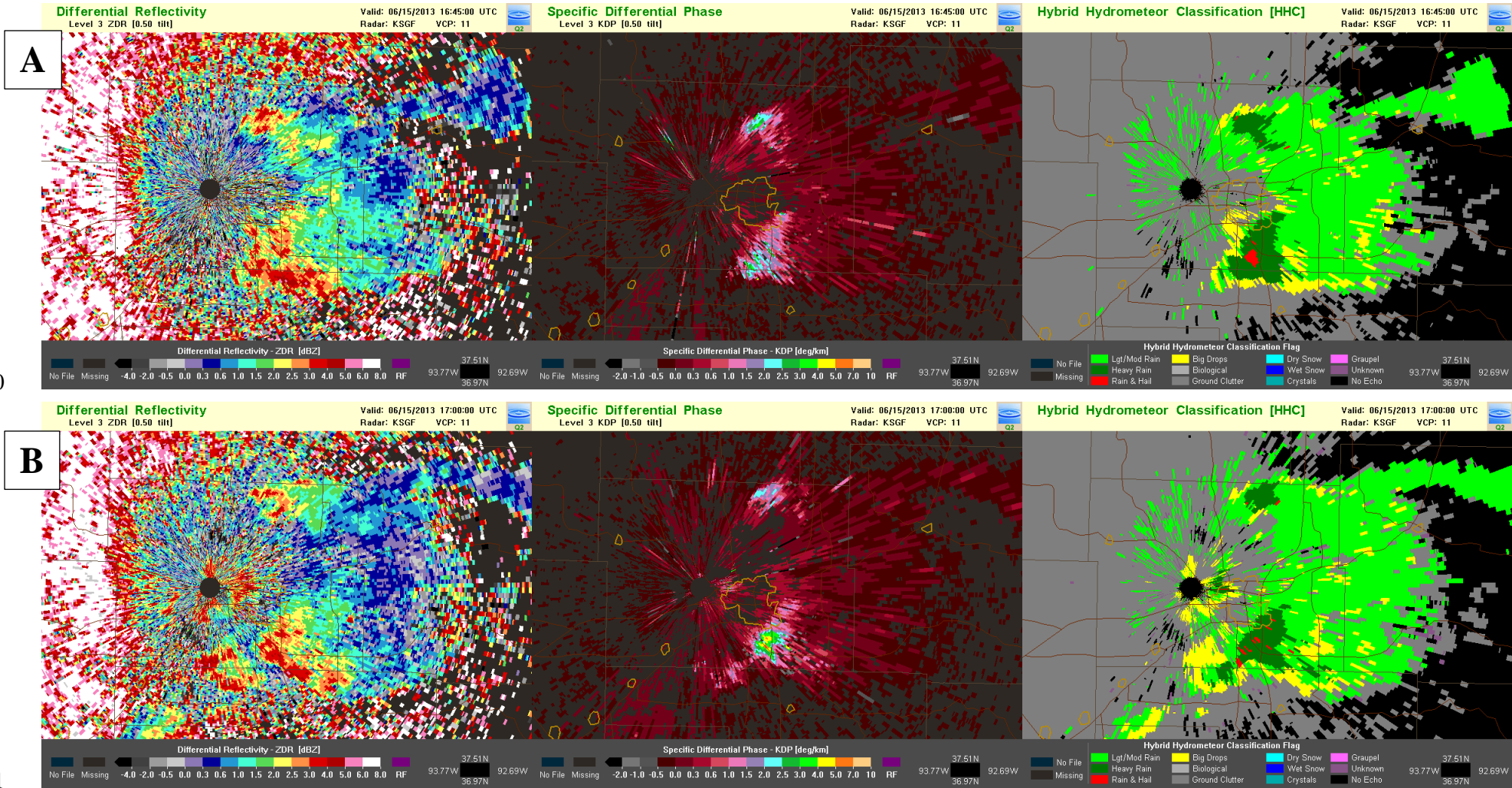


Figure 18. Dual-pol NEXRAD data from site KSGF at 1645 UTC (top row) and 1700 UTC (bottom row) showing differential reflectivity (left column), specific differential phase (middle column), and hydrometeor classification (right column). Data obtained from NSSL's MRMS system. 1645 UTC and 1700 UTC correspond to approximately 30 minutes and 15 minutes of lead time, respectively. The area of heaviest rainfall (between Springfield and the Greene/Christian county line) is experiencing heavy rainfall mixed with hail just prior to the onset of flooding.

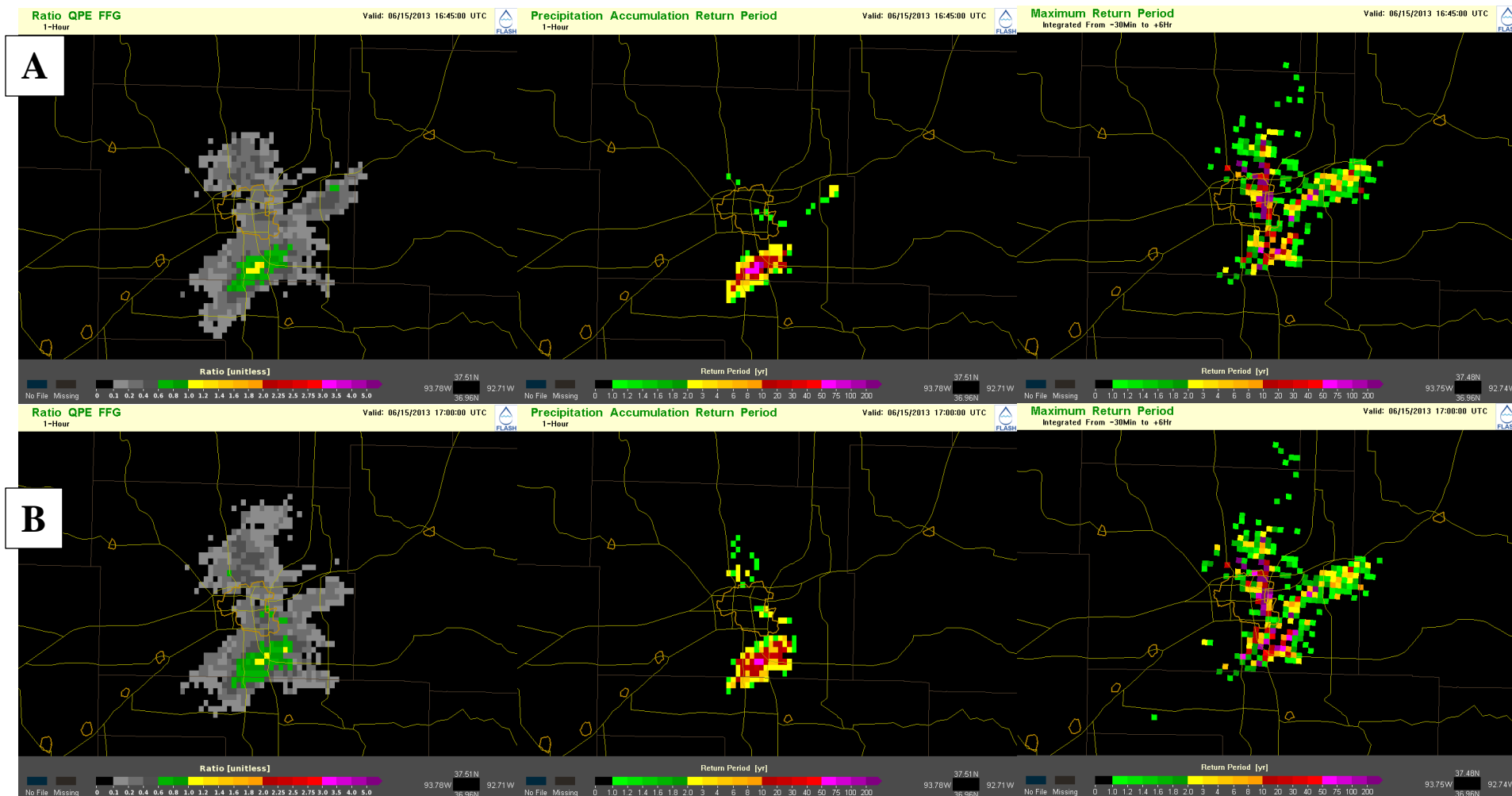


Figure 19. One hour GFFG ratio (left column), one hour rainfall ARI (right column), and FLASH streamflow ARI for 1645 UTC (top row) and 1700 UTC (bottom row) obtained from NSSL's FLASH system. 1645 UTC and 1700 UTC correspond to approximately 30 minutes and 15 minutes of lead time, respectively. The area of heaviest rainfall (between Springfield and the Greene/Christian county line) is depicted as barely exceeding GFFG but is shown to be at least a 50yr (2% annual chance equivalent) event when compared to historical rainfall frequency data. Streamflow ARIs across many portions of Springfield are exceeding the 50 yr (2% annual chance equivalent) event.

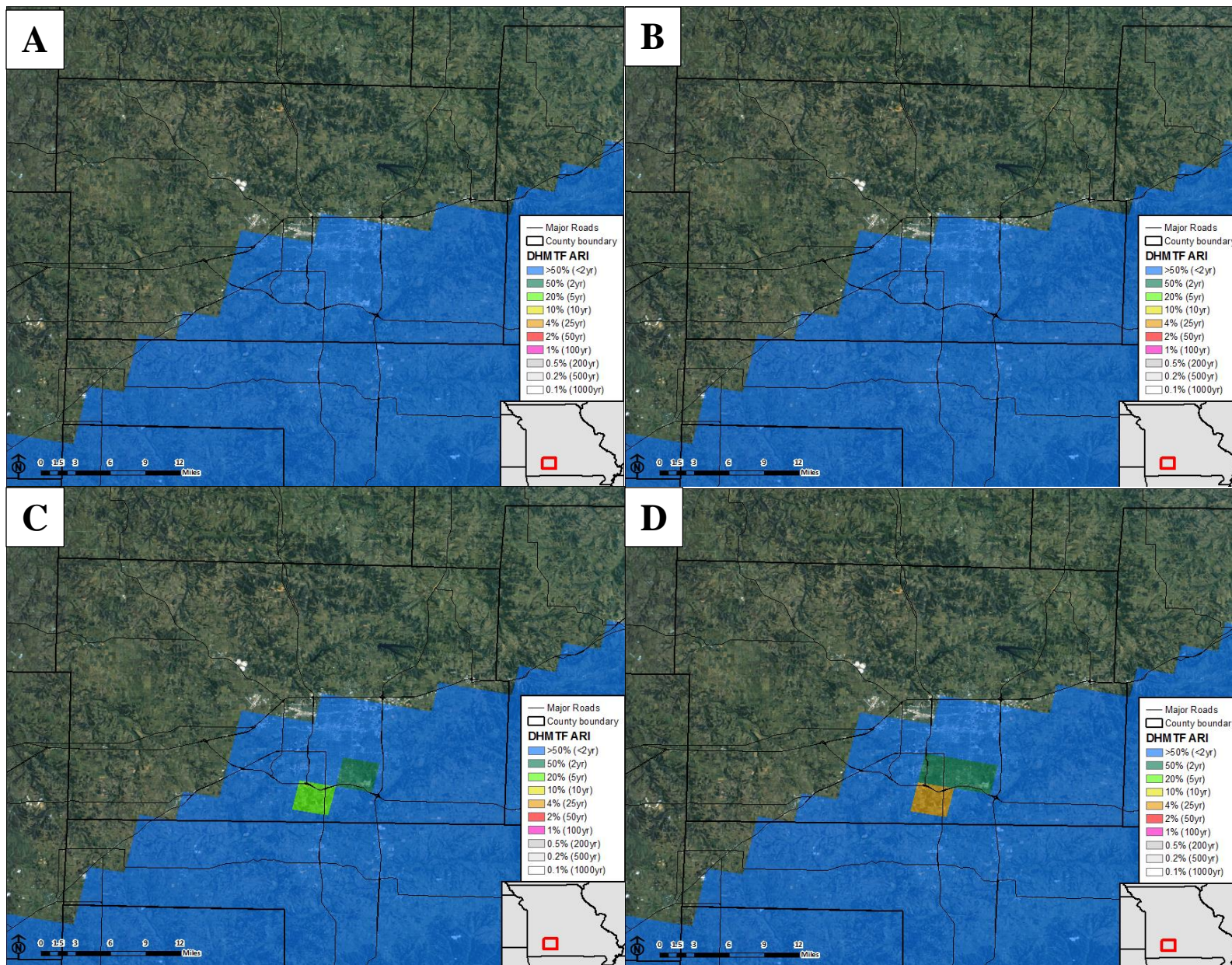


Figure 20. Output from the DHM-TF modeling experiment based upon RFC rainfall estimates up through 16 UTC (A), 17 UTC (B), 18 UTC (C), and 19 UTC (D). Results would be available to NWS forecasters at 50 minutes past the hour.

## 5. Discussion

June 15<sup>th</sup>, 2013, was not a day that forecasters would typically see as favorable for flash flooding. Precipitable water was above average, but not particularly anomalous, based upon nearby sounding data. An outflow boundary from a line of decaying thunderstorms was the focus for nearly stationary, heavy thunderstorms to form over portions of Springfield. Data suggest that these storms were not dominated by warm rain processes as is seen in many missed flash flood events. The slow movement of the storms was the main factor in the extreme rainfall accumulations which exceeded the 100 yr (1% annual chance equivalent) event over two and three hour durations for an isolated area of south Springfield, with a single gauge location meeting the 1000 yr (0.1% annual chance equivalent) event for a two hour duration.

Although the atmospheric conditions did not provide substantial alarm for the potential of flash flooding, the event (including its uncommon magnitude) was somewhat forecastable prior to the onset of flooding. The main tool used by local NWS offices to determine if flash flood warnings are necessary is the GFFG product produced by the NWS RFCs. For this event, the operational GFFG product was not particularly useful. Although rainfall did exceed GFFG values suggesting that flooding was possible, the rainfall barely exceeded the flooding threshold suggesting a marginal event. When looking at experimental rainfall comparisons to historical rainfall frequency data, the magnitude of the event was much more apparent. Even 30 minutes prior to the first report of flooding in the area, the one hour ARI indicated rainfall exceeding the 50 yr (2% annual chance equivalent) event, suggesting flooding of an uncommon, near extreme magnitude.

Analysis of rainfall events in the context of historical rainfall frequency is not a new concept, although this is typically done after an event. During the summer of 2013, the NSSL added in estimates of one and two hour rainfall ARIs to their experimental FLASH site. The rainfall that drives the estimates is the radar-only Q2 product (called Q3 since summer 2013) derived from the MRMS national 3D mosaic of radar data from across the continental United States. Although no bias correction is applied, rainfall data from Q2 has much more frequent updates than rainfall data from NWS RFCs and is available much

more quickly. Rainfall data from NWS RFCs can be up to 1.5 hours old after bias correction and human quality control; in contrast, Q2 data and its derivatives are typically available within 15 minutes. Another benefit to using realtime rainfall ARI estimates is that it can dramatically reduce the area indicated as likely to experience flooding. For the June 15<sup>th</sup> case, every report of flooding except for one was located within the area of at least 2 yr ARI (50% annual chance equivalent), and most of the more severe flooding impacts were in the higher magnitude rainfall ARIs. It should be noted that rainfall severity may not correlate directly to flooding severity - especially on larger scales - due to many factors, including seasonal vegetation differences, soil moisture variability, differences in terrain, and human interaction with natural terrain. Because of this, caution should be used when applying rainfall severity as a proxy for flash flood severity. Usage of radar-only rainfall estimates from Q2 also requires forecaster awareness of potential rainfall biases that could cause an underestimate or overestimate in the ARI products.

Another caveat to using rainfall ARIs (as well as GFFG) as a flash flood nowcasting technique is that it does not contain any routing of runoff to downstream locations. Some flash flood impacts are noted downstream of where the runoff was generated, in some cases being outside of the area of rainfall. Experimental tools such as the DHM-TF and FLASH are being developed to address this issue. Both techniques provide an estimate of streamflow ARI rather than rainfall ARI. Theoretically, output from these models should match most closely to actual reports of flash flooding. For the June 15<sup>th</sup> case, both the DHM-TF and FLASH outputs were less helpful than the rainfall ARIs. DHM-TF did eventually indicate significant ARIs for Ward Creek, one of the hardest hit areas that contributed to a large portion of the flood reports. It should be noted that ARIs greater than approximately 20 years are considered significant with the DHM-TF, as rainfall period of record used to create the baseline frequency analysis was only 10 years. Unfortunately, the DHM-TF output indicating the significant streamflow would not have been available to NWS forecasters until approximately 19 UTC, over two hours later than the first flooding reports. Output from FLASH was available at much more frequent intervals with a much shorter delay, but it indicated many areas of Springfield would experience extreme flooding which did not

509 correlate to a single report. The approximate centroid of the highest ARIs from FLASH also did not  
510 match up with the flood reports.

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## 6. Conclusions and Future Work

The June 15<sup>th</sup>, 2013, flash flood of south Springfield, MO, was caused by an isolated area of very slow moving thunderstorms that produced very heavy rainfall over a three hour period. Best estimates of storm total rainfall from a combination of radar data and numerous rain gauge sites operated by various entities suggest an event with less than a 1% chance of occurring in a given year, also referred to as a 100 year event. Isolated locations may have experienced rainfall within a two hour period of the event that matched rainfall with only a 0.1% chance of occurrence in a given year (1000 year event). This rainfall caused the flooding of several creeks in the area that impacted multiple major arterial roadways and at least one residence.

This flood event is yet another case that demonstrates the need for multiple flood forecasting tools and techniques. For this event, almost all techniques, both traditional and experimental, had limitations. Some techniques provided a reasonable estimate of flood severity, but data would not have been available to forecasters before the onset of flooding. Other techniques indicated flooding, but yielded many areas of false alarms. For this event, the technique that appeared to best match both the location and severity of flooding was the rainfall ARI product, although it should be expected that the best-performing technique will vary by event.

As with meteorological forecasting in the NWS, realtime nowcasting of high impact hydrologic events will be greatly improved with the availability of multiple tools and techniques, used by a trained, critically-thinking forecasting staff, in realtime. Useful warnings require not only a statement on the possibility of an event, but a reasonable estimate of the event magnitude. Flash flooding continues to be one of the biggest threats to lives and property in the U.S. The NWS should continue to support new tools and techniques to address the threat.

## 7. Acknowledgements

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